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Mathematical modeling of electromechanical characteristics of linear electromagnetic and induction-dynamic motors

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Abstract. The calculations of the electromechanical characteristics of the pulse action linear motor (PALM) with cylindrical symmetry are performed. The case of the motor power from the capacitor bank of a given capacitance is considered. The model of "field-circuit" was used for electromechanical characteristics modeling. The electromagnetic field was calculated by finite difference method taking into account the displacement of the secondary element (SE). The problem of circuit theory was solved together with the field problem (via flow coupling) in order to determine temporal dynamics of the current and voltage. The current and voltage in the primary circuit of the PALM, the force in the SE of the PALM, the value of the SE displacement was calculated for each time point. It is shown that the electromechanical characteristics depend on the design and material of the SE.

Keywords: electromagnetic field, vector potential, induction-dynamic motor, the electromechanical characteristics, pulse action linear motor (PALM), cylindrical symmetry model.

1. Introduction

Recently electric devices of pulse action with forward movement of the working element are intensively developed. Such devices must be direct drive, since they are used to create a large forces.

Most suitable in this case are two types of PALM – electromagnetic motor and induction-dynamic motor (IDM). Depending on the SE stroke length, the SE end speed, the number of cycles per unit of time the effectiveness of aforementioned types of engines is different. To select the type and design of PALM it is necessary to have the methods for calculating their characteristics, as well as quantitative estimates of their parameters. The aforementioned quantitative estimates are impossible to obtain without learning the peculiarities of distribution of magnetic flux in the PALM. The electromagnetic and induction-dynamic linear motors impulse actions with cylindrical symmetry are considered.

2. Relevance

Issues of experimental and theoretical studies on the application of electromagnetic PALM of are the subject of numerous works [1-5, 10-14]. Technological processes, e.g. in the construction, mining and metallurgical industries require the implementation of short-term shock effects, which can be implemented by using of the electromagnetic PALMs.

3. Statement of the problem

In this study, the task of mathematical modeling of electromechanical processes occurring during operation of the electromagnetic PALMs with cylindrical symmetry when they are powered by a capacitor bank.

4. A mathematical model

For the solution of the field task cylindrical coordinate system was used, and the cylindrical symmetry of considered model exists.

In this case, the system of equations of the electromagnetic field can be reduced to one equation [6, 7]

$$-\frac{\partial}{\partial r}\left(\frac{A}{\mu r}+\frac{1}{\mu}\frac{\partial A}{\partial r}\right)-\frac{\partial}{\partial z}\left(\frac{1}{\mu}\frac{\partial A}{\partial z}\right)+\beta\frac{\partial A}{\partial z}+\alpha\cdot\left(\frac{A}{r}+\frac{\partial A}{\partial r}\right)+j\cdot\omega\cdot\gamma\cdot A=J\,. \qquad (1)$$

Here $\beta=-\gamma\cdot w$ and $\alpha=-\gamma\cdot v$; γ - is the specific conductivity of the material; v, w- are components of the velocity of the SE; A, J - are φ–components of the vector potential of the electromagnetic field and density of the external current, respectively.

Components of magnetic induction are described by equations

$$B_r=-\frac{\partial A}{\partial z};\;\; B_y=\frac{A}{r}+\frac{\partial A}{\partial r}.$$

The value of the induced current is described by equation

$$J_{in}=-\gamma\cdot\frac{\partial A}{\partial t}.$$

Ponderomotive force, acting on the SE is described by equation

$$F=F_y=B_r\cdot J_{in}.$$

To solve the equations of the electromagnetic field (1) the finite difference method, which took into account displacement of the SE and the induced currents in the SE of is applied.

Further, the PALM power from the capacitor bank is considered. His capacity is 1600 mkF and the initial voltage is 1000 V. The resistance of the circuit was equal to 0.125 Ohms and inductance 0,021 H. The equation of an electric condition of the primary circuit would be

$$\begin{cases} U_c=R\cdot i+\dfrac{d\Psi}{dt} \\ i=C\cdot\dfrac{dU_c}{dt} \end{cases}. \qquad (2)$$

Here R, C, i, U_c, Ψ – the resistance, the capacitance, the current in the circuit, the voltage on the capacitor and flux linkage, respectively.

The integration of the system of differential equations (2) was performed by the Runge-Kutt method (see e.g. [8]).

The joint solution of the field problem (1) to determine the vector potential and then Ψ, as well as the circuit problem (2) to find i and U_c allows to trace the dynamics of changes of the electromechanical characteristics of the motor and the SE displacement.

According to Newton's second law the displacement y of a secondary element (armature, his weight is m) under the force of F over time t was determined by integrating the equations corresponding to

$$m\frac{d^2y}{dt^2}=F\,.$$

5. The simulation results

Further, the model of armor electromagnetic PALM [9] is considered. Winding is located in the cavity between the core and the armature, it has 780 turns. The PALM has two working gap value δ.

The experimental dependences of the tractive force $F(\delta)$ at a constant value current of 5 A is shown in Fig.1. It also shows the calculated curves obtained with and without the saturation of the stator and armature. You can see that taking into account the saturation of the ferromagnetic parts leads to a significant decrease of tractive force in the region of small gaps (about 2 times) and improved convergence of experimental results and the results of the calculations. It should be noted that at small gaps the stator, upper and lower parts of the armature are the most saturated as a consequence of their smaller thickness compared to the central part of the armature.

Further, the calculation of electromechanical characteristics of an IDM is considered. It is assumed that the IDM power from the capacitor bank. The capacitor bank initial voltage and the active electric resistance of the primary circuit are known. The design scheme of the IDM is shown in Fig.2. The mass of the armature is 50 kg.

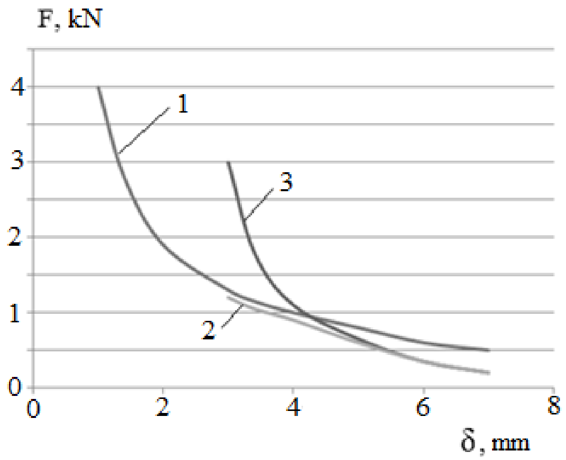

Figure 1. The dependence of the tractive force from the value of the air gap δ. 1 - experimental data [9]; 2, 3 – the results of the calculations with and without the saturation respectively

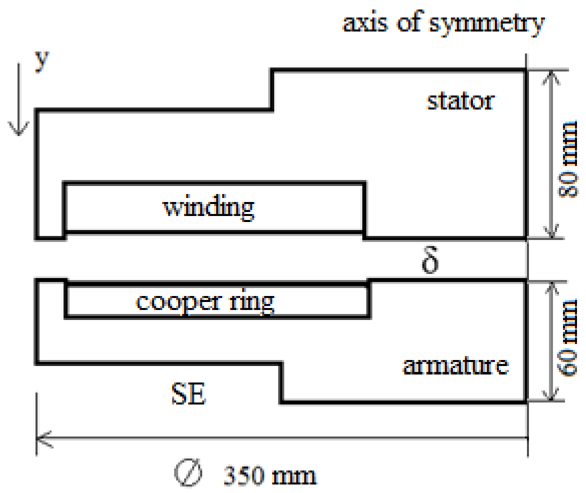

Figure 2. The design scheme of the IDM

A study of the influence of the copper ring thickness in the secondary element on the electromechanical characteristics i, U_c, y, F IDM was performed. The calculation results are shown in Fig.3-6. The basic version in these figures is identified by the number «0». It corresponds to the thickness of the copper rings of 6 mm. The rest material of the secondary element is a steel with a relative magnetic permeability of 10 and a specific conductivity of about 5 times lower than that of copper. The number «1» corresponds to a secondary element of non-magnetic steel with a conductivity of approximately 5 times lower than that of copper. The number «2» corresponds to the basic version, but with increased to 8 mm thickness of the copper ring. The number «3» corresponds to the basic version, but with reduced up to 4 mm thickness of the copper ring.

According to the results of the study using the SE without cooper ring leads to a slower decrease in voltage (Fig.3), to a smaller the displacement of the SE (Fig.4), to a less force on the SE (Fig.5), to a smaller current in the primary winding (Fig.6). Increasing the thickness of the copper ring results in larger force on the SE (Fig.5) and correspondingly to larger displacement of the SE (Fig.4). Reducing the thickness of the copper ring leads to the opposite effect.

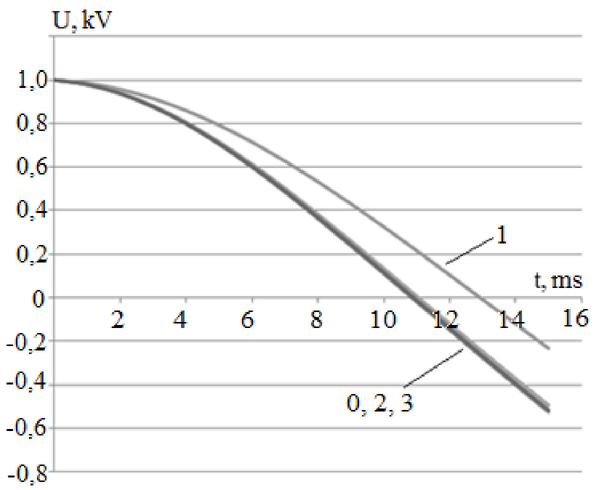

Figure 3. The time dependence of the voltage in the primary winding

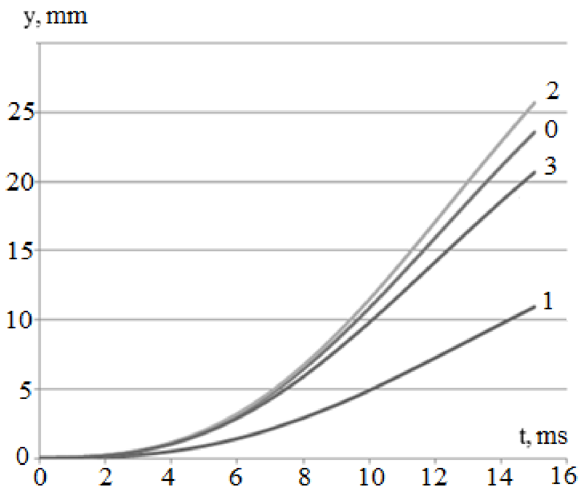

Figure 4. The time dependence of the SE displacement for different designs

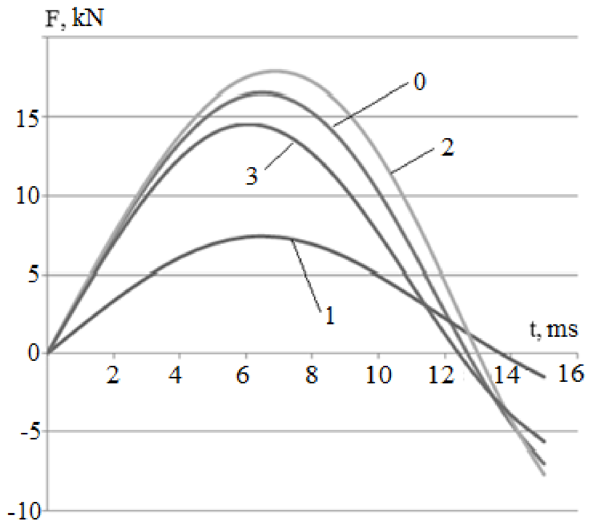

Figure 5. The time dependence of forces acting on the SE

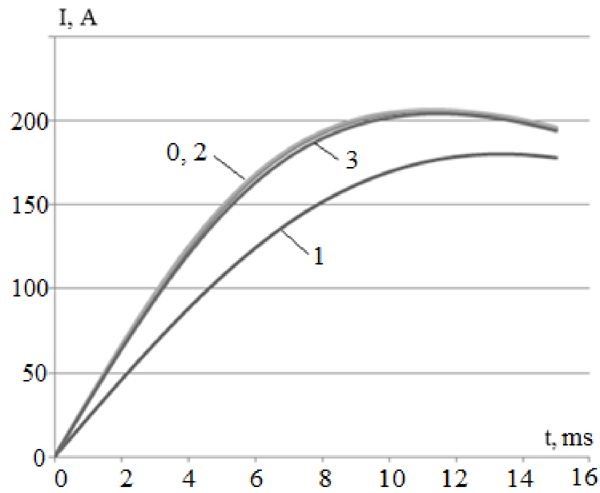

Figure 6. Time dependence of current in the primary winding

6. Conclusions

1. The mathematical model "field-circuit" to describe the electromechanical characteristics of the PALM is constructed.
2. It is shown that the increasing of the SE copper ring thickness leads to increase of force acting on the SE from the magnetic field created by the primary winding.
3. The design of the SE has a significant influence on the electromechanical characteristics of the PALM.

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